

Artificial Inertia Assisted Automatic Load Frequency Control for Power Systems with High Renewable Energy Integration and Accurate Prime Mover Dynamics

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Abstract

This paper presents simulation and analysis of automatic load frequency control (ALFC) with various prime-mover models with renewable energy sources (RES) added to the system. Comparison between actual (re-heat) and approximate (non-reheat) model of prime-mover has been done for single control area where a solar system has been delivering power to load with thermal power. With increase in adding the renewable energy sources in interconnected system, frequency control becomes an important task to full fill because renewable (especially solar PVs) do not have any inertia like thermal plants. This may cause inaccurate assessment of frequency deviations which may further affect the performance of power system. The approximation in the mathematical modelling of governing system for the prime-mover model can be eliminated by this analysis which proves that reheat model is more accurate than non-reheat model. The control at the point of RES inclusion ensures best suitable scenario for both renewable and thermal power. Finally, the inertial support missing in the renewable is obtained with Artificial Inertia Control which mimics the performance of conventional generator to support frequency. Simulation results has been compared with various prime-mover models in MATLAB / SIMULINK. This analysis will help to assess stability of the system especially when a renewable energy source has been integrated with conventional power with artificial inertia support. This research emphasis on correct assessment of frequency with actual prime mover models with effect of integration of RES on frequency assessment and artificial inertia which makes the ALFC more robust in various conditions.

Keywords: Artificial Inertia, Automatic Load Frequency Control, Prime Mover Models, Renewable Energy Sources.

Introduction

Normally, the power systems operate in a where constant frequency and voltage profile gives proper system reliability and from that it can be said that main two controls are there in power system i.e., voltage control (local control) and frequency control (global control). As the frequency of the entire system is same, it is controlled globally and hence it is called global control. On the other hand voltage is not same at all stages of particular system and hence it is called local control (1). Generation usually comprises of thermal, hydro, nuclear and gas as well as renewable units for the interconnected power system. Automatic load frequency control (ALFC) of non-isolated power systems is defined as the regulation or control of power output of generators within a specified area with compare to change in system frequency, tie line loading to maintain scheduled system frequency and/or established interchange

with other areas of interconnected power system within predetermined limits (1). The role of prime mover also plays a vital role for the change in frequency after any disturbances. With larger size of the prime mover, the impact of reheater, steam chest and piping also need to be considered. This gives healthy load frequency control with all parameters are considered (2). Furthermore with increasing integration of RES in the system it becomes more important to control frequency in a better way to have stable and reliable operation of interconnected power system as these RES do not have inertia support like conventional thermal or hydro plants (3). In order to achieve integrated operation of the large and complex power system it is required to maintain system frequency and voltage profiles within prescribed limits. Due to less requirements of generation, prime-mover models used in past were simple turbine systems

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with no reheat sections and also in small size. As the power requirements are increasing day by day it is necessary to use higher order prime-mover models with proper number of reheat sections (2). As the single area control captures all the dynamic analysis of system like inertia, damping, governor-turbine and speed regulations with proper traceable analysis it can be used as a benchmark for the analysis of artificial inertia and micro grid studies. Once the behavior of the system is analysed it will become easier to add multiple area in the analysis in the future work. The main limitation for single area system is coordination issues between neighboring control areas. However, the obtained analysis can be further applied for the multiple area system for the future work.

In the country like India with the current day scenario, it is necessity to have environmental sustainability, energy security, economic development and rapidly growing load demand. This will give rise to the importance of high penetration of renewable energy sources in the interconnected power system (4). India has very large rapid growth in population as well as in industrialization and urbanization which results in higher load demand that cannot be fulfilled by only conventional power plants like thermal and hydro (3). Generally, integration of RES in a power system reduces the fossil fuel dependency, maintaining the power system more reliable and easy to make the balance between load generation and load demand (5). With this high degree of RES integration in the power system, the role of automatic load frequency control becomes more crucial. This is because it does not only have to control the frequency but also need to take in to the account the effect of RES integration. This leads to critical complexity issues in the ALFC which is operated in coherency with the artificial inertia.

The main aim of this research work is to analyse and evaluate an artificial-inertia-assisted automatic load frequency control (ALFC) scheme

that enhances frequency stability in terms of frequency deviations in power system with high renewable penetration. To this end, an aggregated prime-mover model, renewable energy sources and an artificial inertia controller are integrated into a single-area ALFC framework and their combined impact on transient frequency deviations is analysed. The study in this research paper is as follow. The mathematical model with RES for ALFC is analysed in methodology section where controlling RES at the point of inclusion with artificial inertia is addressed. Further the simulation and results are obtained and discussed. Lastly, the findings and future aspects are highlighted for the advancement in ALFC.

Methodology

Figure 1 shows the working diagram of basic control loops that is the primary and secondary loops of ALFC with approximated prime-mover model and its mathematical representation. The primary loop is speed governing system that senses variation in speed due to variation in frequency when load changes and it will react accordingly. On the other hand the secondary loop controls the ALFC system (6). A renewable energy source is considered as shown in the Figure. So, the total generation will be thermal and RES added and load disturbance will be considered as step change. Difference in generation and load will be given to the generator load model which further gives the frequency deviations. With basic PI control in the secondary loop, zero steady state error can be achieved in the frequency deviations (7).

The performance of system can be decided from the values of these time constants and hence it is important to keep them intact within the limits. The gains for prime mover and governor are taken as one. As the change in load occurs the governor mechanism will act accordingly and controls the input steam valve as shown in Figure 1. The change in frequency wrt change in load is provided by the droop D.

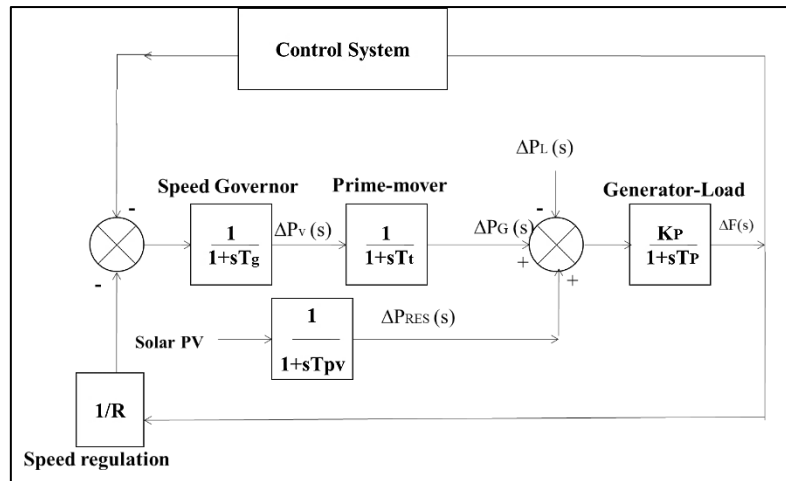


Figure 1: Basic Block Diagram for ALFC Control Loops

The elimination in steady state error can be achieved by PI control. The power system model can be represented as Equations [1] and [2]:

$$K_P = (1/B) \quad [1]$$

$$T_P = (2H / B*f) \quad [2]$$

Equation [1] shows the modelling of generator load of the system and Equation [2] shows time constants of this gen-load model. Here B is damping co-efficient that represents change in power demand with change in frequency and at times this can be neglected as its value is less.

The prime-mover also known as turbine model in ALFC ensures the balance between power produced and the load requirements by adjusting the mechanical power which is based on frequency deviations. In order to maintain system reliability, stability fluctuations in frequency this process of prime-mover is important. The prime mover is basically a mechanical system in thermal and hydro power plants that converts energy into mechanical power which drives the generator. In block diagram shown here in Figure 1 approximation is taken in the prime mover modelling with an approximation has been considered in the time constant of prime-mover where reheating, cross over piping and steam chest time constants are not considered (8).

The generic arrangement of prime mover analysed. Basically, prime movers are placed either in tandem compound or cross compound manner. Here generator and prime mover is arranged in a single shaft for tandem compound and two generators are arranged in two shafts in cross compound. Non-reheat and reheat are the types of prime-movers where for less power non-reheat is used and for more power reheat systems with

either cross compound or tandem compound are used. There is main four stages in the prime mover operation: VHP, HP, IP and LP. Fraction of total power generation would be summation of all these four units which is unity. As shown in figure all the parts of prime mover require its own time constant which is not considered in approximated prime mover models.

Tch, Trh and Tco are the time constants that represent delays due to different process in the prime mover like the cross over piping, steam chest, re-heaters and inlet piping.

In the considered steam turbine model, the steam chest is represented by a time constant of 0.3 s, the reheater by a time constant of 10 s and the crossover piping by a time constant of 0.5 s. The total mechanical power is divided among the turbine sections such that 40% is produced in the high-pressure (HP) stage, 30% in the intermediate-pressure (IP) stage and 50% in the low-pressure (LP) stage. For comparison purposes, a non-reheat prime mover is also modeled using a single effective time constant of 0.35 s, which aggregates the dominant turbine dynamics into a lower-order representation (3).

The main objective is to analyse the transient frequency behavior and the importance of advancement like artificial inertia in the ALFC under various load and RES disturbances. Hence the validation is carried out with time domain simulations for different range of operating

scenarios. While this approach is commonly adopted in automatic load frequency-control and micro grid studies, it does not provide explicit quantitative stability margins; a more exhaustive stability assessment is thus left for future work (9). A typical target has been set by various countries for integrating RES and India is in the range of 20 to 30 percent as reported previously (10). Different countries have set different future targets in raising the integration of power from RESs like PV and wind power plants (11). These future aspects will help in balancing generation and rapidly increasing load demand as well as it will help in reducing the pollutions (12).

These renewables do not have higher inertial response as we have in conventional power plants like thermal. For wind power plants also the turbines are connected through semiconductor converters and hence it will not directly help in the inertial response like thermal (13). Hence the more we integrate RES in the system the more will be reduction in the system inertia (5). This will result in to high frequency deviations in the system (14). A different penetration levels of RES were presented and used with a Synchronous Generator (SG) to cover 3.8 MW load demand (7). As reported in that literature, the rate of change of frequency will increase with increase in RES integration.

Synchronous inertia starts acting on short time scales and has range from milliseconds to tens of seconds. The impact on frequency stability and short-term stability i.e., rotor angle stability will be seen with this reduced inertia. Secondly, with high percentage integration of RESs reserve capacity reduces as inertial support is missing. Therefore the frequency deviation will be on the higher side and to eliminate such issues a new frequency control technique is required to be served by RES as discussed in earlier investigations (10).

Moreover, specific applications, such as solar water pumping for irrigation, offer high efficiency and cost savings compared to conventional

methods, making RES practical for targeted use cases (15). However, challenges persist, such as the fluctuating output from large solar PV plants, which can create grid stability concerns. While energy storage helps mitigate these issues, it also adds significant cost, especially when fully charged storage offers no additional profit to the system owner. Therefore, optimizing the balance between generation, storage and grid integration is crucial for maximizing the benefits of renewable energy systems while minimizing costs and operational risks (16). To effectively integrate RES with conventional power plants, proper prediction of wind and solar PV generation is needed. Advanced forecasting algorithms and real-time control systems must be prepared to maintain RES output and other generations accordingly otherwise the system could face unwanted frequency deviations due to sudden mismatches in power generation and load demand (17). In order to have proper operation of interconnected power systems in the regards of frequency control especially when more RESs are integrated following solutions are analysed in this research:

a) Controlling RES at the point of injection

The load demand in the power system can be fulfilled by obtaining power from both conventional power plants like thermal and renewable like solar (17). Fraction of power from both types of generation is added together. As shown in Figure 2 the load disturbance in the grid is taken care by both thermal and RES. The frequency deviation signal is taken as feedback with controller placed between grid and RES at the point where RES power is injected. This controller controls the power injection of RES and according to the frequency deviation it gives signal to inject the power from RES (18). The balance between both power generations is achieved in an optimum manner with the help of this controller. A PID control is used for this purpose which helps in obtaining proper and accurate frequency control with ALFC in the system (19).

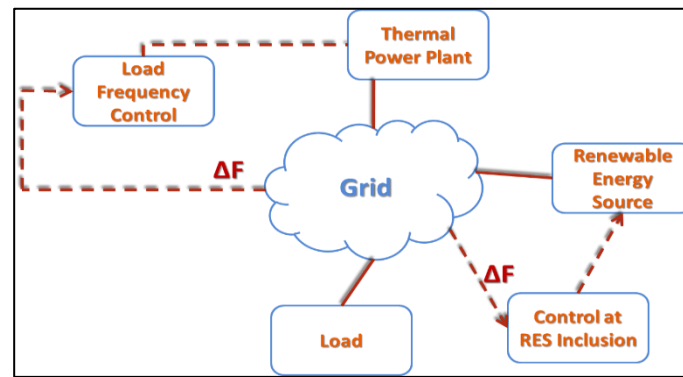


Figure 2: Control at the Point of RES Injection Without Artificial Inertia

b) Artificial Inertia Control

Renewable Energy Sources do not have its own inertia like conventional power plants as discussed. This will disturb the frequency control with more integration of RES in the system adversely. With the advancement in power electronics devices and converters it is possible to mimic the initial operation of conventional power generation like thermal power plant i.e. making battery storage system to behave as inertia during initial phase of ALFC operation (20). This concept is known as Artificial Inertia or Virtual Inertia control. Artificial Inertia delivers the power which

is required due to change in load or change in frequency. Basically, it imitates the conventional generator's performance but artificially. This control operates for initial phase of ALFC only and the time period varies from 5 to 10 seconds as which is similar to inertia in conventional generator. Energy storage systems like Batteries are used in combination with various algorithms and RESs and gives the proper control to ALFC. This advancement helps ALFC to have accurate and stable operation of power system when large amount of RES is integrated (21).

The total inertia of the system that combines both conventional (Synchronous Generator) and RES (Virtual Generator) can be obtain using the H_{eq} (22) as represented in Equation [3].

$$H_{eq} = \frac{\sum_{i=1}^{SG} H_i \cdot S_{Bi} + \sum_{j=1}^{VG} H_{Vj} \cdot S_{Bj}}{S_B} \quad [3]$$

In above Equation [3],

H_i = Inertia of Synchronous (Conventional) generators

H_v = Inertia of Renewable Energy Sources

S_{Bi} = Rated Power of Synchronous (Conventional) generators

S_{Bj} = Rated Power of Renewable Energy Sources

S_B = Rated Power of the Power System

For the same amount of load demand as the integration of RES increases, the overall inertia of the system decreases which further affect the frequency control adversely.

For 15 MW of total power generation the

equivalent inertia will change as the amount of power changes from both solar and thermal. As given in the Table 1, with more power sharing from solar, the equivalent inertia is also more and decreases as RES power increase.

Table 1: Equivalent Inertia during Power Sharing by Conventional and RES

Conventional Power (MW)	RES Power (MW)	H_{eq} (MW*s)
12	3	0.7114
11	4	0.6521
10	5	0.5929
9	6	0.5336
8	7	0.4743
7	8	0.415

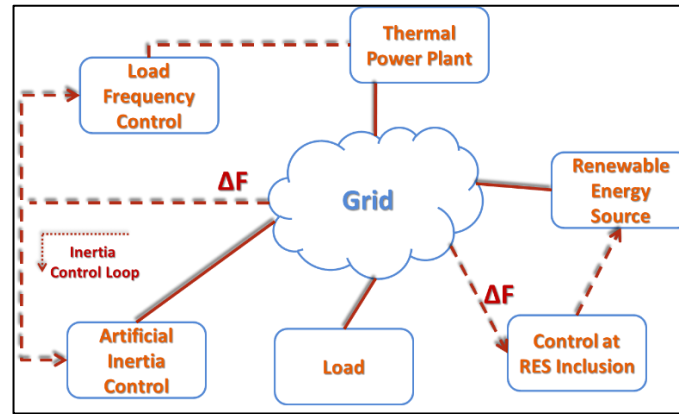


Figure 3: Control at the Point of RES Injection with Artificial Inertia

The concept of artificial inertia control is derived to improve the power system frequency control to have accurate and stable operation as shown in Figure 3. With change in load the frequency of the system changes and this signal is given to artificial inertia control. As per the change in load this control gives signal to energy storage system to deliver power in proportion with change in load. The time required by the artificial inertia control is T_{AI} . The transfer function model analysis is used for this purpose (20).

In most artificial inertia studies, inverter and converter dynamics are neglected because the analysis is done at a reduced system level focused on primary/secondary frequency dynamics. Here the inner current/voltage control loops and PWM operate much faster and can be approximated as ideal actuators or simple first-order lags. This

abstraction has become standard practice in benchmark-type ALFC and artificial inertia work, while more detailed converter studies explicitly model inverter dynamics but typically pursue converter/control design and stability questions rather than high-level frequency-control performance (23). Hence in order to have time scale separation and model tractability, the analysis is bounded with the transfer function modelling.

In this work, artificial inertia is implemented as a derivative-based control loop acting on the active-power reference of the inverter/ESS. The system frequency is measured by the controller with respect to ROCOF and injects additional active power required in the system due to change in load.

$$\Delta P_{inertia}(s) = \frac{K_{AI}}{1+sT_{AI}} \frac{d\Delta f(s)}{dt} \quad [4]$$

Equation [4] gives mathematical representation of artificial inertia power in Laplace domain where K_{AI} and T_{AI} are artificial inertia gain and time constants respectively.

The design of K_{AI} and T_{AI} follows the tuning procedure as: First, a baseline automatic load frequency control loop without artificial inertia is analysed. Then, the artificial inertia gains are increased gradually and evaluated by the simulations under step load changes and RES fluctuations with the aim of reducing frequency deviations with acceptable settling time. The artificial inertia controller is designed and validated single area system with small signal models which limits the stability analysis of the system (20).

In this study, higher order nonlinearities in the ALFC model are neglected and a fixed droop with sufficient spinning reserves is assumed, so that the

primary frequency response can be represented using standard linear transfer functions. The renewable energy source is modeled by a transfer-function representation characterized by an effective gain and time constant using low-order dynamic models, since such reduced-order descriptions are generally adequate for frequency-control analysis at the system level. Variations in solar power and load demand are treated as external disturbances acting on the islanded microgrid and the artificial inertia controller is implemented as a derivative-based scheme that uses the rate of change of frequency (ROCOF) to inject an additional active-power component into the

microgrid power reference during contingencies (24).

A single area power system with actual and approximated prime mover model is considered in this study follows the standard ALFC benchmark model commonly used for controller design and comparison in the literature; the governor-turbine-generator parameters are adopted from these benchmark studies. For prime mover models, an IEEE Dynamic report is used to design the reheat and non-reheat prime mover models (2). The conventional ALFC loop was first implemented and its step-response characteristics (frequency deviation and settling behavior) were checked against published results for this benchmark system to validate the Simulink model before introducing the proposed artificial-inertia-assisted ALFC scheme. The conventional ALFC response (without artificial

inertia) was first reproduced and checked against typical frequency-deviation profiles reported in these works, to validate the Simulink implementation before introducing the proposed control scheme.

Figure 4 shows the analysis in the simulation form for actual and approximated prime-mover models. In the simulation of actual prime-mover model, the tandem compound arrangement has been considered whereas in approximated model the non-reheat system is considered. Non-reheat system and tandem compound prime mover models are analysed and compared and remaining parameters are not kept same for both the case. Furthermore, the integration of RES and Artificial Inertia Control is also simulated with ALFC to analyse the impact of RES in the frequency deviations.

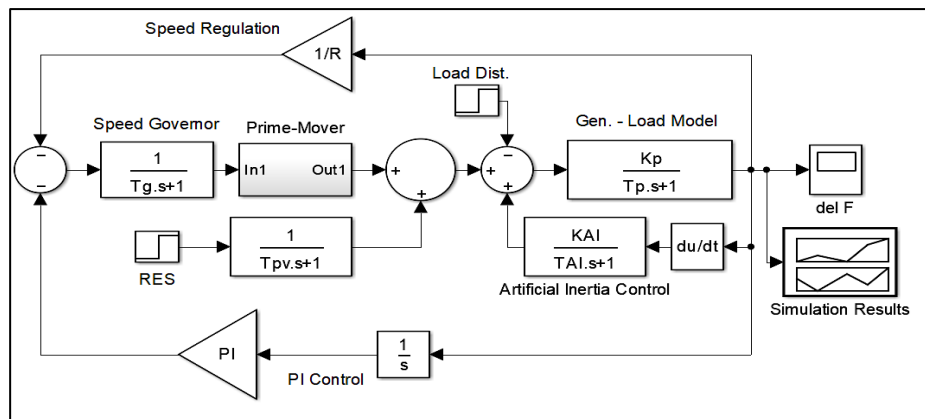


Figure 4: MATLAB Model of ALFC with RES Integration and Artificial Inertia Control

In the simulation of ALFC with RES integration and different prime mover models, the load disturbance is considered as step change in load of 10% in the system. This load disturbance can be

taken care by the thermal and PV power as shown in the Figure 4 and Table 2 gives the system parameters.

Table 2: System Parameters

Parameter	Value
Time Constant of Governor T_g (s)	0.1 s
Time Constant of Turbine	
Steam Chest Time Constant T_{CH} (s)	0.1 s
Re-heat Time Constant T_{RH} (s)	4 s
Cross Over Piping Time Constant T_{CO} (s)	0.3 s
Integral Control Variable Gain K_i (s)	0.05
Droop Constant R (Hz/p.u.MW)	2.4
Damping Coefficient D (p.u. MW/Hz)	0.015
System Inertia H (p.u.MW s)	0.083
Artificial/Virtual Inertia Control Gain K_{AI} (s)	0.5
Artificial/Virtual Inertia Time Constant Based ESS T_{AI} (s)	10 s

Solar System Time Constant T_{pv} (s)

1.8 s

With approximated prime-mover model system frequency deviations can results into unstable but for the same system parameters actual prime mover (where all the time constants have been considered) model will give stable operating conditions in context with frequency deviations. Hence the predication of the stability of the system will became inaccurate in approximation in the prime-mover modelling. Therefore, the use of actual prime mover models is better where all the time constants are considered for accurate assessment of the system.

As per the standard ALFC benchmarks (e.g., $T_t = 0.5s$ $T_g = 0.2s$ $R = 0.05$ p.u. $R = 0.05p.u.$, $D = 0.8$) the turbine-governor parameters are selected. The ALFC gains are tuned by minimizing an integral error of the frequency deviation over representative load and RES disturbance scenarios, following common ALFC tuning practice. The physical inertia coefficients are computed from generator ratings, while the artificial inertia and damping gains are chosen through a parametric search (or optimization) that targets improved nadir and ROCOF under severe disturbances.

A statistical analysis of the time-domain response is carried out using standard control performance indices, namely peak overshoot, settling time,

steady-state error and integral error measures for the frequency deviation. The load disturbance is considered as step change in load and the integration of renewable is considered as step signal. The Artificial Inertia is added with and without PI control at the point of inclusion of RES. Lastly, the frequency deviations are analysed with and without Artificial Inertia in the system. The simulated results correspond to the average of all cases, providing a compact statistical summary of the Artificial Inertia control with prime mover dynamics.

Results

In this section the effect of approximation in the analysis of ALFC is observed in terms of frequency deviations.

Actual and Approximated Prime-mover Model without RES Integration

Initially an approximation in prime-mover model is considered and Figure 5 shows the result of approximated prime-mover model (blue line). Furthermore, when actual model of prime-mover was analysed it can be observed that due to all the time constant (T_{ch} , T_{rh} and T_{co}) we can have exact deviations of frequency. Hence, we can get accurate analysis of frequency with actual prime-mover model.

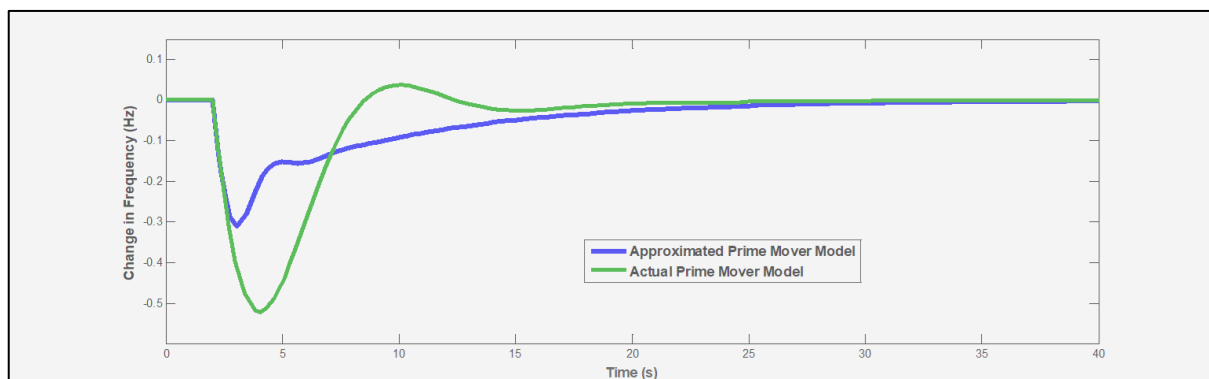


Figure 5: Frequency Deviations with Actual and Approximated Prime-mover Models Without RES Integration

Effect of Reduction in Inertia on Frequency

As mentioned earlier that with integration of RES in the system, for same power capacity the overall inertia reduces. This will cause more problem in the frequency control especially with Solar PV

power plant. From Figure 6 it can be observed that with reduction in inertia during the RES integration frequency deviations will be more in during initial cycles. This is because RES has no inertia support for frequency deviations. Hence larger size integration of RES power plant is limited due to frequency control.

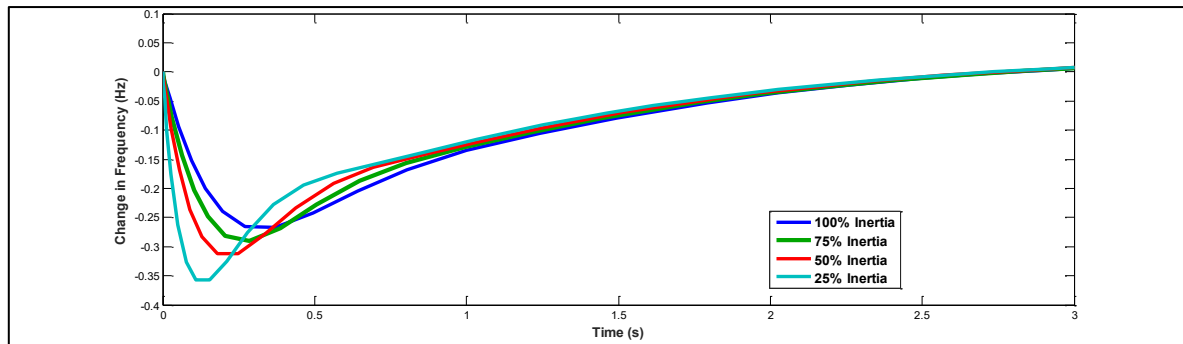


Figure 6: Effect of Reduced Inertia (Due to RES Integration) in System Frequency

Effect of % Increase in RES Integration on Frequency Deviations

Due to missing inertial support for the frequency deviations, it is difficult to integrate entire capacity of RES directly to the system. This is observed in the further analysis that with increasing in RES percentage in the system, the frequency deviations will also increase and after certain amount of

integration frequency relay may get tripped due to larger frequency deviations. For the same amount of load disturbance as we increase the RES in the system, frequency gets disturbed largely as observed in Figure 7. Hence it is very important to control the frequency during RES integration so that system stability in terms of frequency deviations can be maintained.

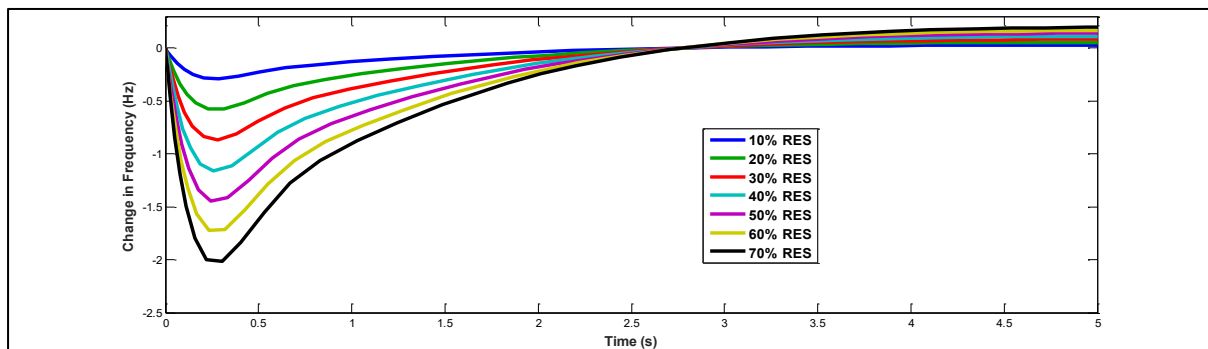


Figure 7: Frequency Deviations with Increase % of RES

Actual and Approximated Prime-mover Model with RES Integration (Normal Case)

The complete power system analysis has been made where a step load disturbance has been taken care by both thermal and RES with actual and approximated prime-mover models. An inaccuracy in the frequency deviations can be observed as

shown in Figure 8 with approximation in prime-mover models even with RES integration. With same other parameters, it was observed that approximated model gives more damping in the frequency control and also it will take more time to settle. Hence in order to get accurate analysis of frequency deviations in it can be concluded that actual prime-mover should be used.

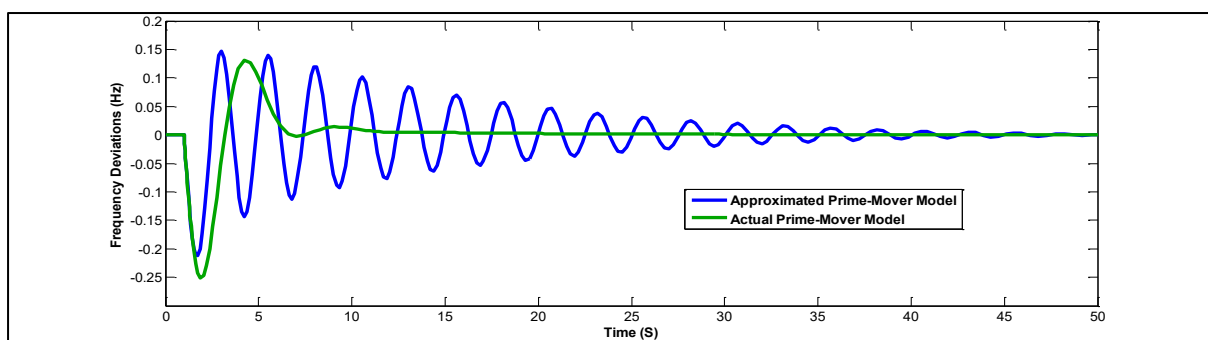


Figure 8: Frequency Deviations with Actual and Approximated Prime-mover Models with RES Integration

Actual and Approximated Prime-mover Model with RES Integration (Worst Case)

A special case has been considered where approximation can lead in to completely wrong frequency analysis. As shown in Figure 9, there is a possibility that even though the system is stable

with RES integration the wrongly approximated prime-mover model can give such unstable results shown by blue line. Here the time constant taken in approximated prime mover model causes unstable system response. This can be considered as worst-case scenario in the analysis of automatic load frequency control as it gives absolutely wrong assessment of frequency deviations.

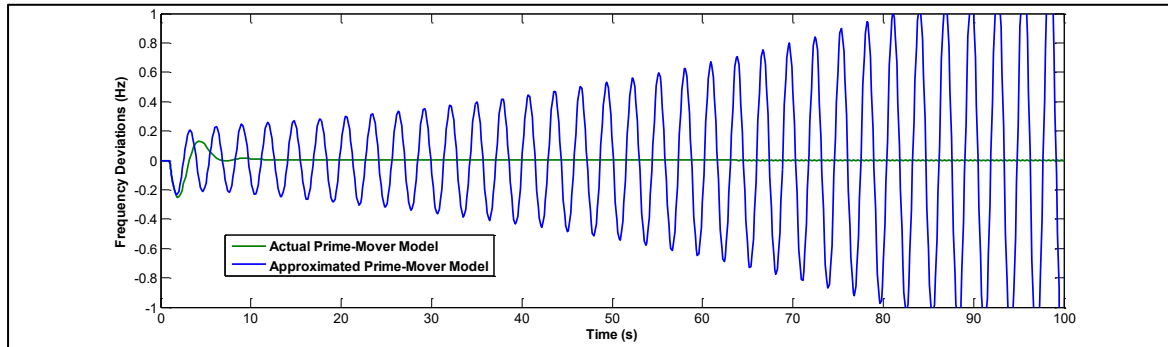


Figure 9: Frequency Deviations with Actual and Approximated Prime-mover Models with RES Integration (Worst Case Scenario)

With and without PID Control at RES Integration (without Artificial Inertia)

The frequency control in ALFC becomes more complex with integration of RES and in order to have proper control we can add PID controller the point of RES injection in the system. PID control provides fine control of frequency deviations as it

gives appropriate signal to the RES for the power injection. As shown in Figure 10 the controller at the point of injection helps in reducing the frequency error shown by green line. This advancement in the RES integration provides proper operation of power system in terms of frequency deviations.

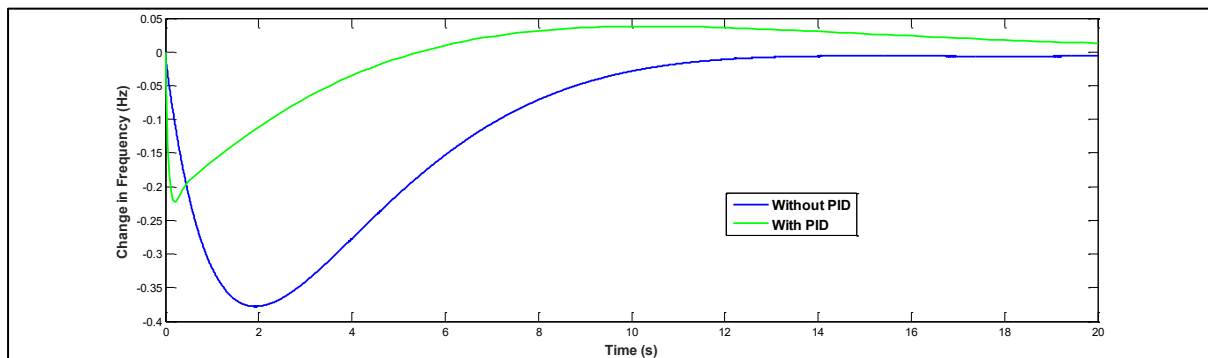


Figure 10: Change in Frequency with and without PID control at the point of RES Injection for 10% Step Change in Load (without Artificial Inertia)

With and without PID Control at RES Integration (with Artificial Inertia)

When Artificial Inertia is added in the system as shown in the block diagram earlier, it helps system frequency control. Energy storage systems like batteries, ultra capacitors etc. are used to obtain the artificial inertia. Initial few seconds after the

load disturbance is the time when artificial control comes in to the picture to help the frequency control. Figure 11 shows the comparison of ALFC during RES integration with and without PID control with and Artificial Inertia control is connected in the system. It is clearly observed that with PID control and artificial inertia in the system, frequency deviations can be reduced.

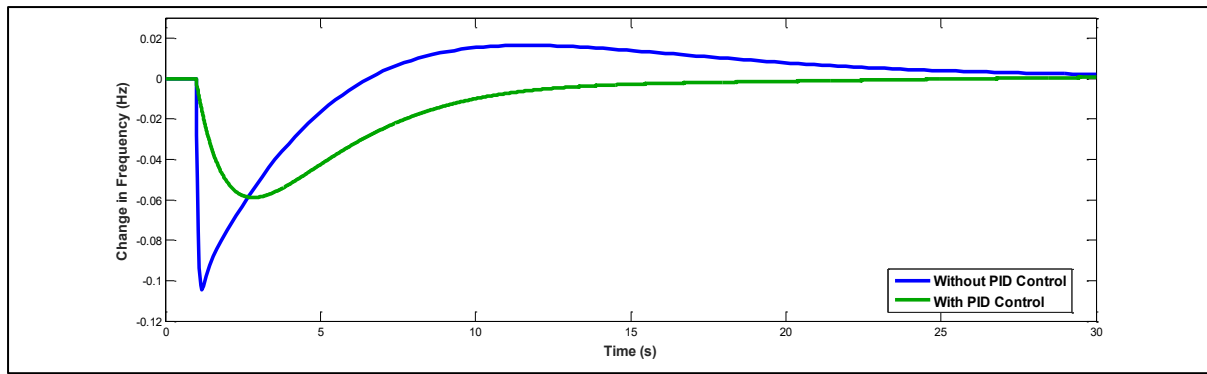


Figure 11: Change in Frequency with and without PID Control at the Point of RES Injection for 10 % Step Change in Load (with Artificial Inertia)

With and without PID Control at RES Integration (with Artificial Inertia) Considering 50% Step Change in Load

The sudden load increase in the power system results in large in generation-load imbalance. Frequency deviations are larger under such conditions which can further leads to instability. Figure 12 shows the frequency response when the load is suddenly increase to 50% (step load

change) with RES integration and artificial inertia included. As shown in the results without PID control, the system exhibits larger frequency deviations and prolonged oscillations. In contrast, the PID controller effectively reduces the frequency deviation, improves damping and restores the nominal frequency more quickly. The inclusion of artificial inertia further limits the rate of frequency change, resulting in enhanced frequency stability.

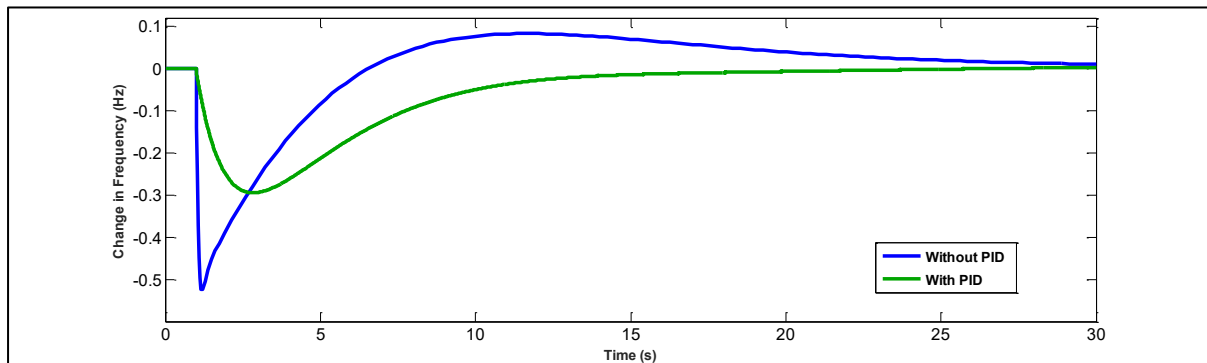


Figure 12: Change in Frequency for 50 % Step Change in Load (with Artificial Inertia)

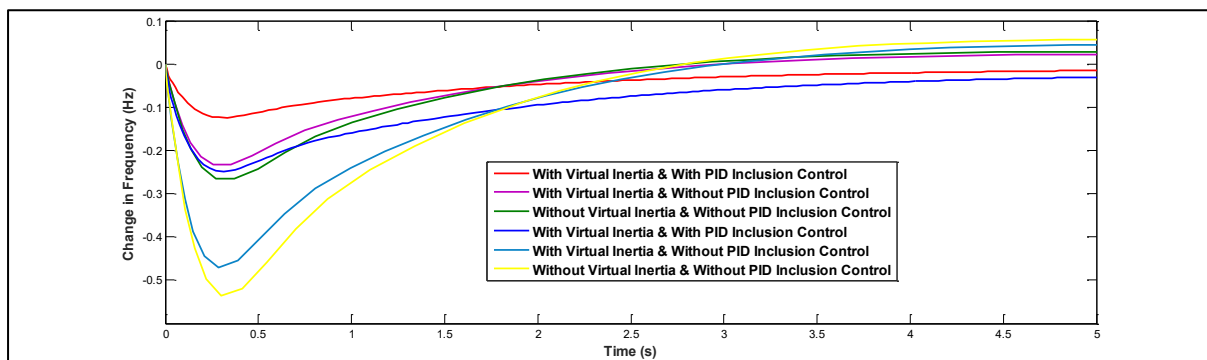


Figure 13: Change in Frequency with and without PID and Artificial Inertia Control

With and without Artificial Inertia and Control at the Point of Inclusion

The results obtained from the artificial inertia controller as shown in Figure 13 will directly

impact the future grids where large amount of renewable is integrated in the system. The proposed artificial-inertia-assisted ALFC scheme illustrates how RES/ESS units can actively contribute to system inertia and

primary/secondary frequency support, thereby helping system operators to satisfy future requirements on ROCOF limits, frequency nadir and response times in low-inertia power systems.

Discussion

The simulation and analysis of ALFC with and without prime mover model demonstrate that the proposed method helps improving the assessment of frequency deviations when a sudden load change occurs. This can be understood by considering the operation of frequency relay where 3 percent change in frequency can trigger the operation of relay which further stop the system operation. The approximated prime mover model gives inaccurate assessment of frequency deviations because the approximation is achieved by considering only one time constant as lumped as demonstrated in other studies (24). On the other hand, the steam chest, reheater and crossover piping need their own time constant. Due to these time constants overall time required to correct the change in frequency increase and hence in accurate results are seen (25). Results states that with actual prime mover model ALFC can work in healthier manner because it represents actual scenario of the system. A worst-case scenario is also taken where the approximated model has given unstable results even though the system is in stable condition. Hence both cases are possible with approximated model that reduces accuracy of the system. This result eliminates the use of approximation in the prime mover model and actual model is used in all further analysis in this research and the models as well as values for the time constants are considered as given in past researches (2).

With high degree of RES integration, the overall system inertia reduces which further affects the frequency control badly. The deviations in frequency increase rapidly as overall system inertia decreases with more RES integration. This is because solar do not have their inherent inertia like thermal which causes problems during initial few seconds of frequency control. Moreover, results also shows that higher the % of RES more will be the frequency deviations. Both results clearly gives an idea of how RES integration affects the frequency of microgrid (18).

Furthermore, most of the analysis is done controlling the energy storage system where a

controller is placed and change in frequency is analysed (6). In this research a controller at the point of RES integration helps improving system stability in terms of frequency deviations. Results shows a notable difference in frequency deviations with and without PID controller at the point of inclusion. Inclusion of controller at the point of RES integration helps in controlling the frequency. This controller also gives an exact idea about the amount of RES that could be inserted in the grid as the integration is limited (17). The absence of actual inertial control in the RES forces power engineers to analyse Artificial Inertia. The results give clear idea of why Artificial Inertia is important in ALFC when RES is integrated largely. With various testing scenarios, the controller helps in reducing the ROCOF and settling time. At the same time, the study relies on a reduced-order single-area model where the tie line power exchange cannot be analysed. This aspect can be considered for the future work in this area with considering the non-linearities in the ALFC models.

Conclusion

When renewable energy sources (RES) are integrated with automatic load frequency control, overall system inertia reduces which intern makes the ALFC control more complex and difficult. With approximation taken in the prime-mover model we have observed that assessment of frequency deviations can be inaccurate. The elimination of approximation in prime-mover model analysis gives correct and accurate assessment of frequency deviations with and without RES integration. The analysis can be extended further by considering non linearities in the generator load models. From all the result achieved through the simulation and analysis observed here, it can be concluded that approximation in prime-mover model leads to inaccurate assessment of frequency deviations which may further affects the overall stability of the system. Furthermore, with more integration of RES this correct assessment of frequency becomes more important aspect which can also be concluded from the analysis done here. Lastly, Artificial Inertia Control analysed for the precise performance of the ALFC in terms of the frequency deviations. These advancements in the ALFC improves the performance of the system drastically. The study can be further extended by considering multiple area power system where tie-

line power exchange can also be analysed with artificial inertia control.

This study is limited to a single area control for ALFC with RES and artificial inertia and interconnected power system is not considered even though the proposed control strategy demonstrates enhanced frequency regulations under various loading conditions. In future work, this approach can be extended to multi area power system to analyse tie line power control, frequency control and artificial inertia control with RES integration.

Abbreviations

AIC: Artificial Inertia Control, ALFC: Automatic Load Frequency Control, AVR: Automatic Voltage Regulator, RES: Renewable Energy Sources, ROCOF: Rate of Change of Frequency, VHP: Very High Pressure, VSG: Virtual Synchronous Generator.

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Author Contributions

Parin Hasmukhbhai Chauhan: Conceptualization, Methodology, Modeling, Simulation, Riaz K Israni: Validation, Supervision, Review Editing, Chiragkumar Parekh: Data Analysis, Manuscript Editing, Vishal G Jotangiya: Drafting of Paper Sections. All authors reviewed and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest related to this research. No financial, personal, or professional relationships influenced the study by any means.

Data Availability

Not Applicable.

Declaration of Artificial Intelligence (AI) Assistance

During the preparation of this manuscript, the authors used AI-based tools exclusively for linguistic tuning and grammatical correction, with full oversight by the authors. All scientific content,

data interpretation, analysis and conclusions were developed and verified by the authors. The authors take full responsibility for the content's originality, interpretation and accuracy.

Ethical Approval

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